Dynamical Climatology

On the dependence of climate sensitivity on convective parametrization

by

W.M. Cunnington and J.F.B. Mitchell

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Meteorological Office (Met. O. 20)
London Road
Bracknell
Berkshire RG12 2SZ

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W M Cunnington and J F B Mitchell

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Meteorological Office
London Road
Bracknell
Berkshire, UK Rg12 2SZ

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On the Dependence of Climate Sensitivity on Convective Parametrization

W M CUNNINGTON AND J F B MITCHELL

Meteorological Office, Bracknell, Berkshire, RG12 2SZ, England

Abstract

Two sensitivity experiments in which CO_2 is doubled and sea surface temperatures are enhanced were carried out using a general circulation model to determine the influence of the convective parametrization on simulated climate change. In the first experiment a non-penetrative "layer-swapping" convection scheme is used; in the second a penetrative scheme is used. It is found that the penetrative scheme gives the greater upper tropospheric warming, and the greater reduction in upper tropospheric cloud, consistent with recent CO_2 sensitivity studies, but the changes in radiative heating at the top of the atmosphere indicate that there would be a greater tropical surface warming at equilibrium with the non-penetrative scheme. Other possible explanations for discrepancies between recent studies of the equilibrium climate response to increasing CO_2 are discussed.

1. Introduction

Many aspects of model simulation are sensitive to the parametrization of convection. Comparisons between experiments with increased CO_2 run using different models show that there is less enhancement of surface warming with height in the tropics when convective adjustment is used rather than penetrative convection (Schlesinger and Mitchell, 1987).

It has not yet proved possible to determine which representations of convection are the most realistic. Albrecht et al (1986) compared simulations made using a parametrization of cumulus moisture transports with those made using a standard moist convective adjustment (MCA) scheme. They found that the temperature and humidity distributions simulated with the revised scheme were closer to observed than those obtained with the standard model. However, the vertical temperature profile in the tropics is also sensitive to representation of radiative processes (Ramanathan et al, 1983), and in the version of the NCAR atmospheric model used by Washington and Meehl (1984) (using MCA) the errors in zonally averaged temperature in the tropical troposphere noted by Albrecht et al (1986) are largely eliminated. Thus, the performance of the convection scheme depends to a great extent on the representation of other physical processes.

The general circulation models used in the CO_2 studies reviewed by Schlesinger and Mitchell (1987) differed not only in the specification of convection, but also of radiation, dynamics, vertical grid and so forth. In order to investigate the effect of changes in the convection scheme alone,

we have carried out an idealised climate change experiment using two models which differ only in the convective parametrization. The standard model uses the penetrative convection scheme as in Wilson and Mitchell (1987), and a revised version was constructed using an earlier convective adjustment scheme (Saker 1975). The experiments described here compare the sensitivity to doubled CO_2 with sea surface temperatures increased by 2 K for the penetrative convection and convective adjustment schemes.

2. The Model

The model used is the Met O 20 11-layer atmospheric global general circulation model on a 5° x $7^1/_2$° horizontal grid. It is as described by Wilson and Mitchell (1987), except that sea surface temperatures and sea-ice extents are prescribed from climatology and updated every five days.

In the convective adjustment scheme, dry or moist convective adjustment takes place between adjacent pairs of layers starting from the top downwards. The mass exchanged is assumed to be a linear function of the instability of the layers, and in moist convection the latent heat is assumed to be released entirely at the upper level. Precipitation is evaporated into the layer below until a relative humidity of 80% is reached or the precipitation has been totally evaporated. To obtain an annual mean heat balance close to zero, the relative humidity thresholds for layer cloud were increased, except for bottom layer or high cloud, so as to

predict at all layers full cover at saturation and zero otherwise. Convective cloud occurs whenever convection takes place, at a quarter cover in the upper of the two layers undergoing adjustment.

The penetrative scheme is the original scheme described in detail by Slingo (1985), modified to allow some detrainment into the stable layer below which convection is terminated. The scheme is based on parcel theory modified by entrainment. The parcel is intended to represent an ensemble of buoyant plumes which have different characteristics. Parcel values therefore represent an average over the ensemble. Starting at the lowest model layer, a parcel is raised to the layer above. If the parcel remains buoyant, it is diluted by environmental air and raised to the next level where the process is repeated. If, however, the parcel is no longer buoyant, sufficient air is detrained at the density of the lower level until it becomes so. A limit is placed on such detrainment by requiring that the plume cannot penetrate further than an undilute parcel from the initial level. The environmental air is modified by the detrainment of parcel air, evaporation of precipitation and compensating subsidence. The convective cloud amount is proportional to maximum parcel size during convection, and the depth is determined by the depth of convection. If convection is deep (extending through more than three layers), the convective cloud amount is reduced by a factor of ten in all but the lowest three layers in an attempt to represent deep convective towers.

The main difference between the schemes can be demonstrated schematically using an idealized profile (Figure 1). The penetrative scheme can in principle mix air from the surface to level b, corresponding

to the ascent of an undiluted parcel. The adjustment scheme can only mix to level a, determined by mixing to give a constant equivalent potential temperature subject to conservation of moist static energy. Note that in contrast to a moist convective adjustment scheme (Manabe and Strickler, 1964), neither the penetrative nor the adjustment schemes used here will completely remove instability in a single time step.

3. The experiments

Four integrations were done, all starting at the end of the third November of an earlier simulation, which used the same physics as the control simulations described here and in Wilson and Mitchell (1987) except for higher albedos over sea-ice and land-ice and a minor change in the treatment of penetrative convection. Two of the simulations, MCA1 and MCA2, used convective adjustment and the other two, CSR1 and CSR2, used penetrative convection. MCA1 and CSR1 were controls whereas MCA2 and CSR2 had sea surface temperatures increased by 2K and carbon dioxide was doubled. All simulations completed 39 months, and the results are means for the three years following the first three months.

4. Results

a. The zonally averaged temperature distribution simulated by the penetrative scheme; comparison with observations and other models

The annual mean temperatures simulated using the penetrative scheme (figure 2) are close to those observed in the tropics except near the tropopause, the model being up to 9K warmer than observed at 100 mbs. The model is some 2 to 4K too cold in the troposphere in middle and high latitudes, and over 10K too cold in the stratosphere in high latitudes (see for example Oort, 1983).

The bias towards higher than observed temperatures near 100 mbs over the equator may be due in part to the failure of the model's coarse vertical resolution to resolve the sharp temperature minimum found at the tropical tropopause. The model has a layer extending from $\sigma = 0.125$ to $\sigma = 0.06$ centred at $\sigma = 0.089$ (σ = pressure/surface pressure). Other models show a warm bias at the tropical tropopause. For example Schlesinger and Mitchell (1985) report that both the model used by Hansen et al (1984, layer thickness $\Delta\sigma = 0.071$ centred at $\sigma = 0.105$) and also that used by Wetherald and Manabe (1986, $\Delta\sigma = 0.09$ centred at $\sigma = 0.095$) produce temperatures some 5K warmer than observed near the tropical tropopause. The model used by Washington and Meehl (1984) is almost 10K colder than observed in this region. This may be due in part to the fact that the nearest model layer is centred at $\sigma = 0.074$, extending from 0.132 to 0.042 and so is

displaced slightly above the tropical tropopause. Washington and Meehl (1984) prescribe an emissivity of unity for all cirrus cloud, and this will also contribute to the lower than observed temperatures at this level. (See Ramanathan et al, 1983). All three models are 5 to 10K too cold in the stratosphere in high latitudes, as also found here.

The findings of Albrecht et al (1986) suggest that the models using penetrative convection should be substantially warmer in the upper tropical troposphere than those using moist convective adjustment. Both the simulation described here and that reported by Hansen et al (1984), both of which use penetrative convection, do not appear to be substantially warmer in this region than those reported by Washington and Meehl (1984) and Wetherald and Manabe (1986) using moist convective adjustment. Ramanathan et al (1983) note that changing from "grey" (emissivity <1) to "black" (emissivity = 1) cirrus produces a warming of up to 5K in the upper tropical troposphere. This may explain why Washington and Meehl's results are closer to observed than would otherwise be expected. Wetherald and Manabe (1986) use an emissivity of 0.6 for high cloud. However, zonally averaged temperatures in the lower tropical troposphere are up to 5K higher than observed (Schlesinger and Mitchell, 1985), indicating a steeper tropical lapse rate than found in the other models with penetrative convection, as might be expected. Albrecht et al (1986) comment that although the two convective schemes they

compared produced very different zonal mean convective heating rates, these differences were largely compensated by changes in zonal mean radiative heating resulting from changes in temperature, humidity and cloud.

b. The effect of replacing penetrative convection by convective adjustment

When convective adjustment is used in place of penetrative convection temperatures (Fig. 3a) are generally lower within 40° of the equator with a maximum cooling in the upper troposphere where differences of over 2K occur at 250-500 mb within 15° of the equator. Polewards of 40° latitude the changes are generally less with decreases near the surface and increases above with differences of over 1 K in the stratosphere. Relative humidities (Fig. 3b, calculated from annual means of temperature, pressure and specific humidity) generally decrease above 350 mb. Below 400 mb increases are general except in the tropics where there is an area of marked decreases centred at 700 mb where it extends from 30°N to 30°S. Fig. 3c shows that the changes in specific humidity are dominated by increases in the boundary layer and decreases centred at 700 mb in the tropics. Globally meaned convective rainfall decreases from 2.491 to 1.905 mm day^{-1}. The above changes are consistent with the convective adjustment scheme being less efficient at transporting moisture and heat and producing rain than the penetrative scheme. Globally meaned

large scale rainfall increases from 0.337 to 0.832 mm day^{-1}, consistent with the moister lower atmosphere and approximately compensating for the change in convective rainfall.

The simulation of the geographical distribution of precipitation (Figs. 4a and b) is worse (Fig. 4c shows the observed) when convective adjustment is used; the eastern parts of the sub-tropical oceans are too wet and the wet tropical regions in South America and Africa are too dry.

c. The effect of increasing sea surface temperatures by 2K and doubling CO_2

When sea surface temperatures are increased by 2K and carbon dioxide is doubled the greatest warming (Fig. 5) occurs near 300 mb over the tropics; it is 3.5 to 4.0 K with convective adjustment but increases to between 4.5 and 5.0 K when penetrative convection is used. At the surface the global mean warming (Table 1) is 2.32K for convective adjustment and 2.41K for penetrative convection. The corresponding changes in layer cloud are shown in Fig. 6. There is a general decrease in cloud amount in the troposphere except near the surface, with increases near the tropopause and above. With penetrative convection the increases and decreases are more marked. There are large increases near σ =0.23 in mid-latitudes and σ = 0.189 above the equator which are weaker in the convective adjustment case; similarly there are decreases at σ = 0.317 and 0.718 (Fig 6b) which are less pronounced with the adjustment scheme (Fig 6a).

The greater warming and reduction in cloud at upper levels with the penetrative scheme are consistent with the greater response at upper levels to doubling CO_2 in models using penetrative convection schemes (Hansen et al 1984, Wilson and Mitchell 1987) as opposed to the non-penetrative moist convective adjustment scheme (Washington and Meehl, 1984; Wetherald and Manabe, 1986). Note however that the moist convective adjustment scheme used in the latter two studies, although non-penetrative, differs in some respects from the non-penetrative "layer swapping" scheme used here.

In the equilibrium studies of the effect of doubling CO_2, a warming of 7 to 8K is found in the upper tropical troposphere in models with a penetrative convective parametrization scheme, whereas the warming with moist convective adjustment is only 3 to 4K. The difference in the response is therefore of the same order of magnitude as the differences between the control simulations (section 4a). This is somewhat surprising remembering that doubling CO_2 amounts produces a relatively small perturbation of the climate system. As noted earlier, Albrecht et al (1986) found that differences in convective heating produced by altering the convective processes in a simulation of present day climate were largely compensated by changes in radiative heating. In contrast, it may be that the differences in the response of convective heating to increased CO_2 are amplified by the changes in radiative heating. For example, numerical simulations indicate an increase in the mean height of cloud in the tropics on doubling CO_2 which is more pronounced in models using penetrative

convection (see Wetherald and Manabe, 1986; Wilson and Mitchell 1987). The increase in the mean height of cloud will warm the surface and troposphere due to reduced longwave cooling to space: consequently the additional warming due to this radiative feedback will be more pronounced in models using the penetrative scheme. Of course, there remains the possibility that differences in the model other than the treatment of convection contribute to the discrepancy in the warming of the tropical troposphere.

Table 1 shows that globally the total (layer plus convective) cloud decreases rather more when penetrative convection is used in place of convective adjustment. It also lists various radiation quantities. The decrease in reflected solar radiation due mainly to less cloud is offset by increased outgoing longwave radiation due to the warmer atmosphere and surface, giving only small changes in the heat balance at the top of the atmosphere and at the surface. Note however, that with convective adjustment, the increase in the net downward flux of radiation at the top of the atmosphere is 0.9 Wm^{-2} greater than with the penetrative scheme (Table 1).

The greatest discrepancies in the latitudinal distributions of the changes in the heat balance at the surface and top of the atmosphere occur in the tropics and sub-tropics (Figure 7). There is an increase in surface cooling of up to 6 Wm^{-2} in the experiment with the penetrative scheme, whereas with the non-penetrative scheme values are close to zero (Figure 7b). This suggests that the equilibrium surface temperature change would be smaller with the penetrative scheme, consistent with results from

radiative convective model experiments using prescribed cloudiness carried out by Rowntree and Walker (1978) and others. The penetrative scheme is more efficient in transporting heat and moisture upwards from the surface (see Section 4a), so that the same prescribed increase in surface temperature produces a greater increase in the flux of heat from the surface.

There is one feature of Figure 7b which does not appear to be consistent with the equilibrium changes in surface temperature found on doubling atmospheric CO_2. In both experiments here there is increased surface cooling in the tropics and increased warming in high latitudes, indicating that at equilibrium their polar warming should be greater than that at the equator, leading to a reduction in the meridional gradient of temperature. The changes in Figure 7b suggest that the reduction in meridional gradient should be greatest with the penetrative convection scheme, whereas in equilibrium experiments, the greatest reduction appears in studies using non-penetrative convection schemes (Rind 1987, Wilson and Mitchell 1987). We have not been able to explain this apparent discrepancy.

However, Cess and Potter (1988) found that the sensitivity of the Oregon State University two-level model (Ghan et al, 1982) to imposed perturbations depended on the radiative properties assigned to clouds. Since the models used in the equilibrium studies all use different radiative properties, this may account for the apparent discrepancy. Furthermore, in order to obtain a realistic value of the net radiative flux at the top of the atmosphere when changing from the penetrative to the

adjustment scheme in the present work, the parametrization of cloud was altered. This illustrates the difficulty of designing a "clean" experiment to determine the effect of changing the representation of a particular process: changing the model alters the simulation so that it may be necessary to alter another process to compensate.

5. Summary

Two sensitivity experiments in which sea surface temperatures were increased by 2K and CO_2 amounts were doubled have been carried out using the same model with penetrative and a non-pentrative convection scheme. With the penetrative scheme there is a greater warming and larger reduction in cloud in the upper tropical troposphere, consistent with results from recent equilibrium studies of the effect of doubling CO_2. However, the changes in surface heating suggest a greater reduction in the meridional temperature gradient would occur with the penetrative scheme, in contrast to the recent equilibrium studies. Differences in other aspects of the models used in the various equilibrium studies, and in particular differences in the specified cloud radiative properties may explain this discrepancy.

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Table 1 Global annual means

Convection scheme	Convective Adjustment			Penetrative Convection		
	Control	Anomaly	Difference	Control	Anomaly	Difference
Experiment	MCA1	MCA2	MCA2-MCA1	CSR1	CSR2	CSR2-CSR1
Reflected solar Wm^{-2}	105.94	102.25	-3.69	105.64	101.66	-3.98
Outgoing longwave Wm^{-2}	237.81	240.56	2.75	233.68	237.42	3.74
Total (layer+convective) cloud amount %	50.73	49.63	-1.10	52.55	51.03	-1.52
Heat balance at surface Wm^{-2}	-4.13	-3.62	0.51	1.51	1.28	-0.23
Heat balance at top of atmosphere Wm^{-2}	-0.50	0.44	0.94	3.92	4.17	0.25
Surface temperature K	286.91	289.21	2.30	287.06	289.46	2.40

Figure Captions

1. Idealized unstable profile of equivalent potential temperature (Θw) against height (solid line). The dashed line indicates the profile after repeated application of an adjustment scheme. b denotes the maximum level to which an undilute parcel from the surface can rise.

2. Zonally averaged annual mean temperatures simulated using the penetrative convection scheme (see text). Contours every 10K.

3a. Annual mean change in zonally averaged atmospheric temperature due to replacing the penetrative convection scheme with a non-penetrative version. Contours every 0.5K, areas of decrease are stippled.

b. As a, but for relative humidity. Contours every 2% of saturation.

c. As a, but for specific humidity. Contours every 0.2 g/kg.

4a. Annual mean precipitation using the non-penetrative convection scheme. Contours at 0.1, 1, 2, 5, 10 and 20 mm/day. Areas exceeding 5 mm/day are stippled.

b. As a, but with the penetrative scheme.

c. As a, but derived from climatological observations collated by Jaeger (1976).

5a. Changes in annual mean zonally averaged temperature due to doubling CO_2 and increasing sea temperatures by 2K using a non-penetrative convection scheme. Solid contours every 1K, dashed contours at odd 0.5K intervals, and areas of decrease are stippled.

b. As a, but using the penetrative scheme.

6a. As Figure 5a, but for changes in cloud. Contours every 0.01 of total cover.

b. As a, but using the penetrative scheme.

7. The change in annual mean heat balance (Wm^{-2}).

a. At the top of the atmosphere.

b. At the surface.

due to doubling CO_2 and enhancing sea surface temperatures by 2K. Solid line, with non-penetrative convection; dashed line, with penetrative convection.

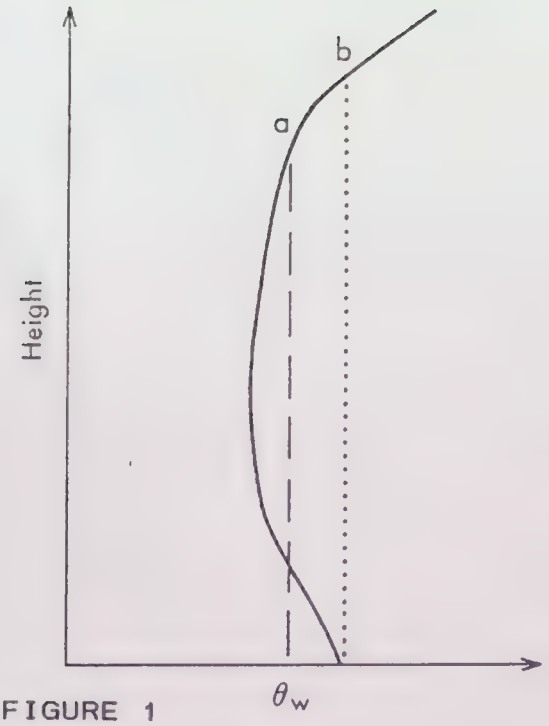

FIGURE 1

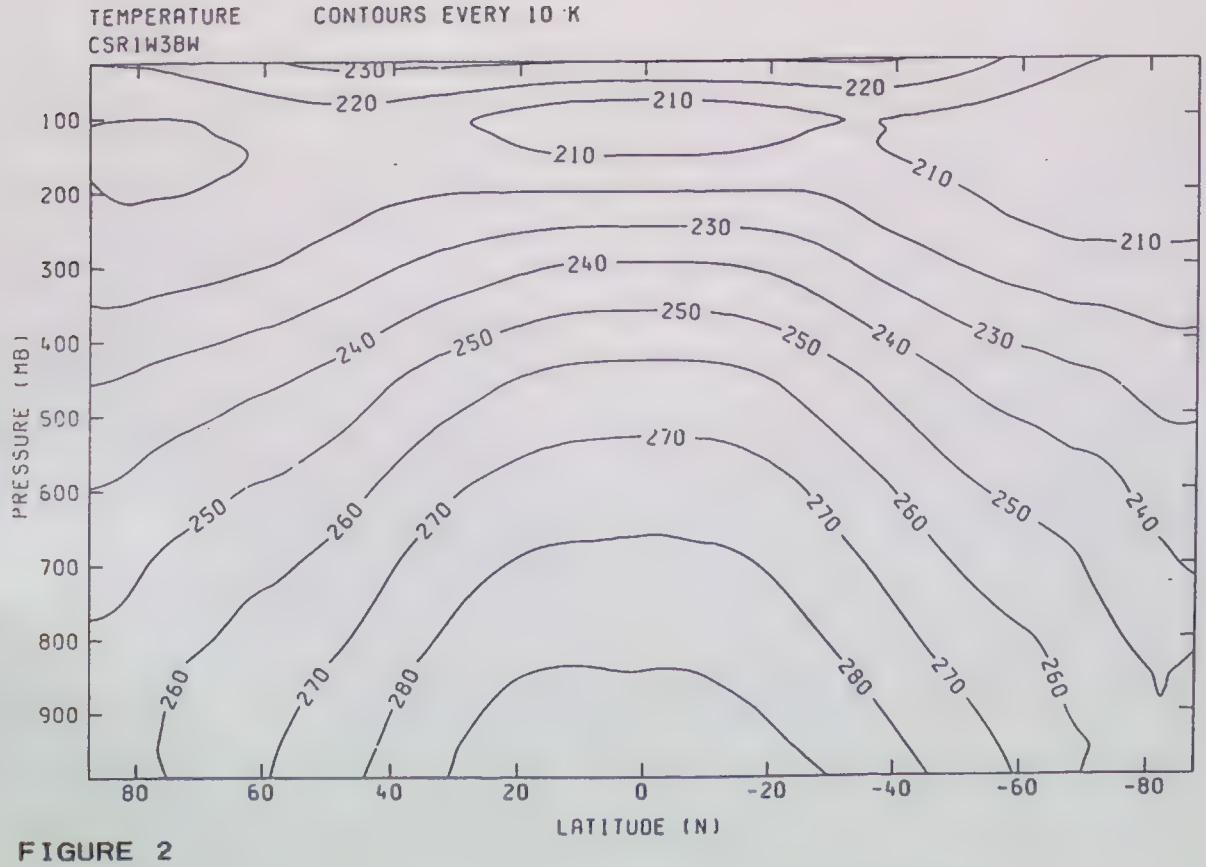

FIGURE 2

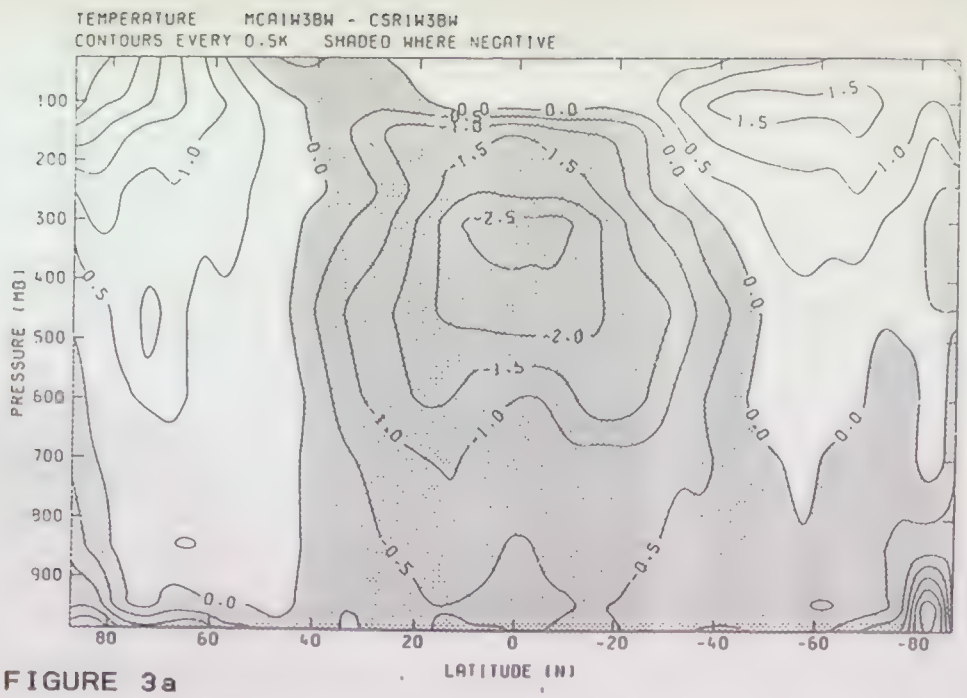

FIGURE 3a

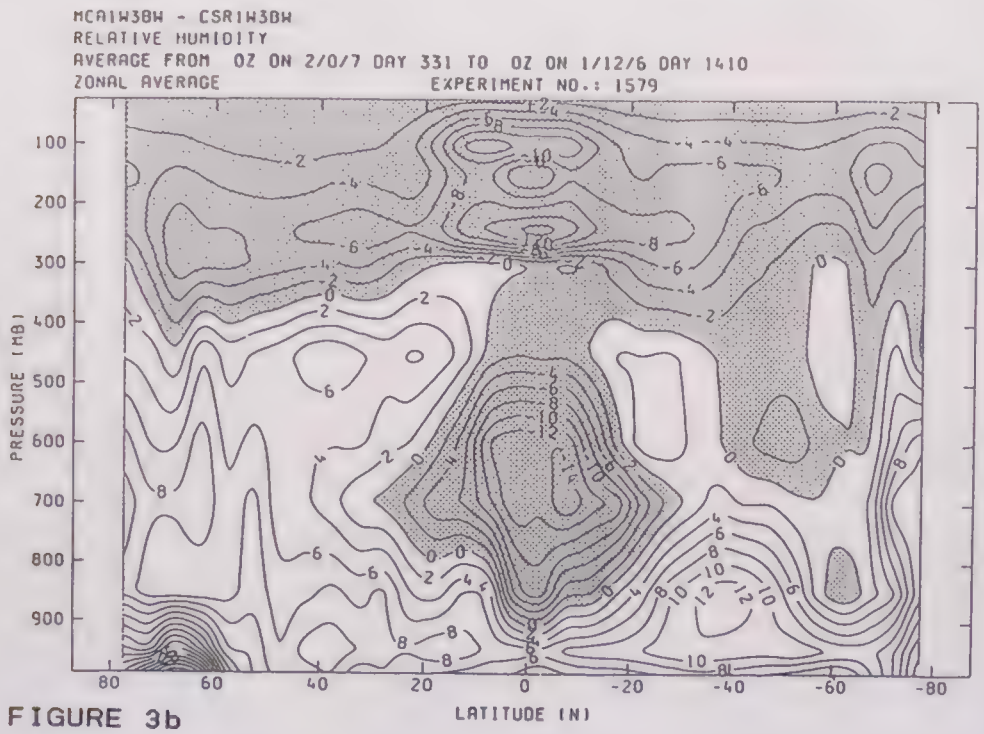

FIGURE 3b

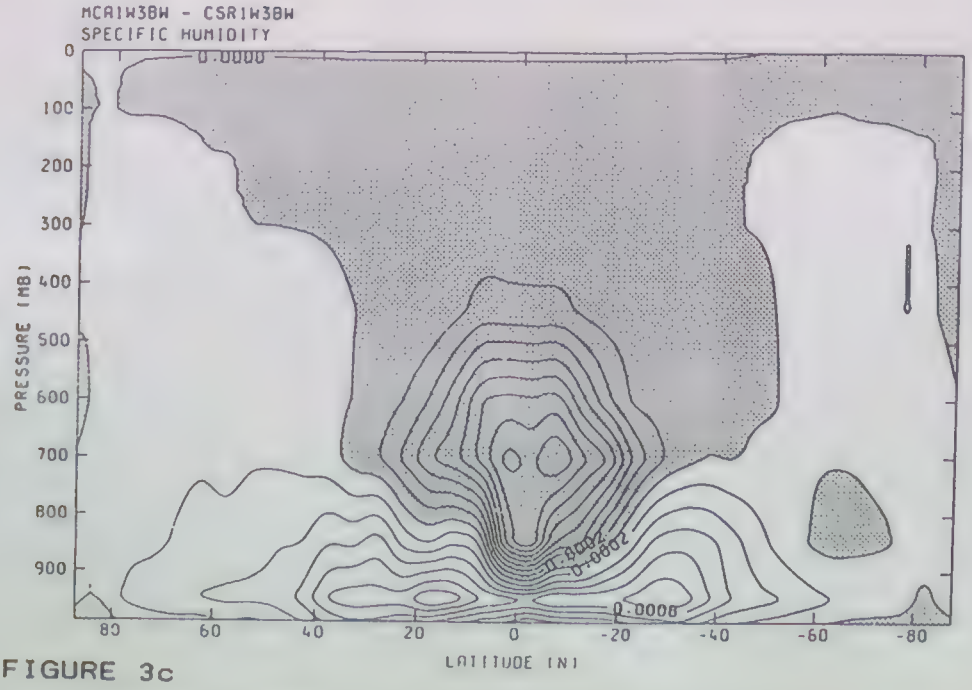

FIGURE 3c

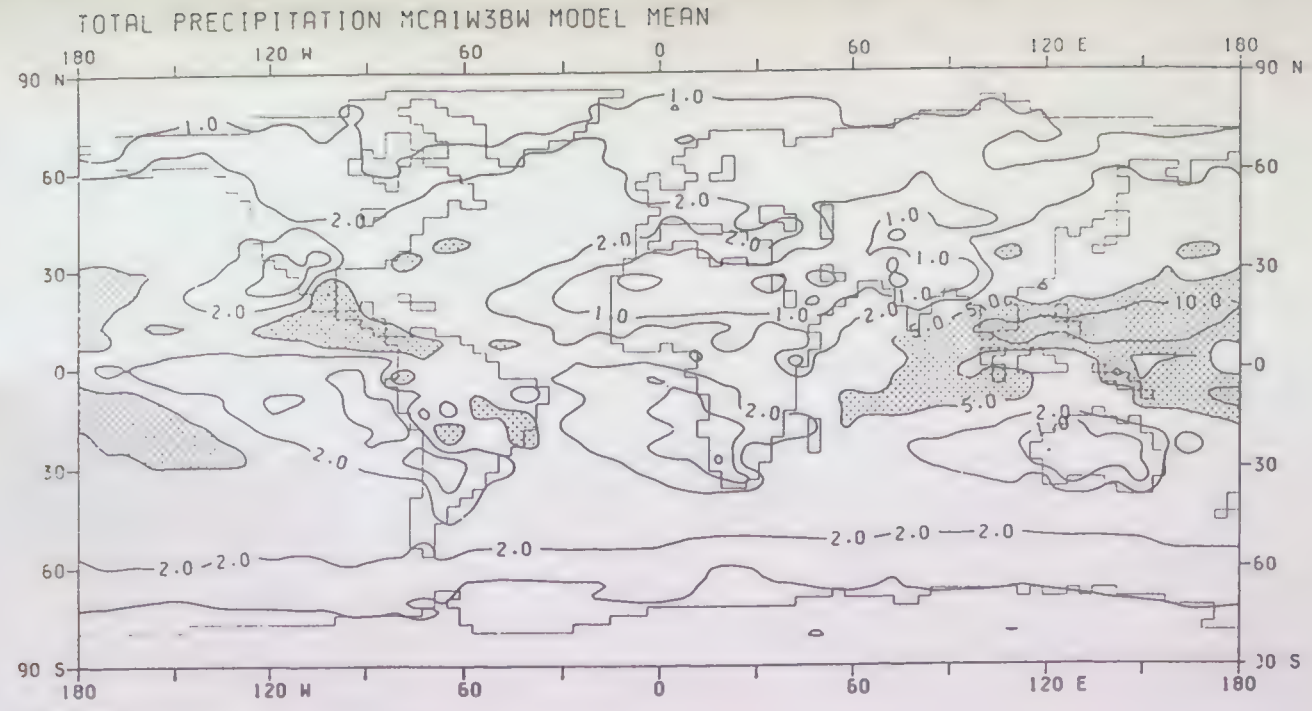

FIGURE 4a

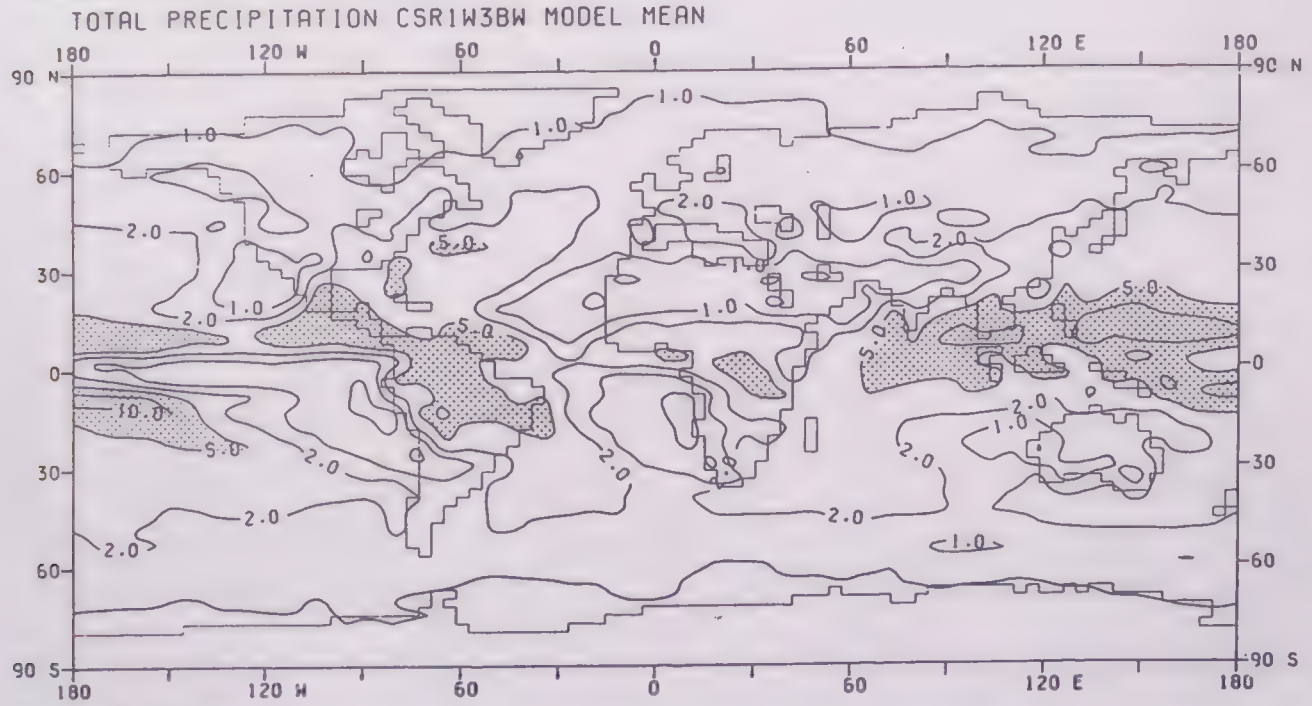

FIGURE 4b

PRECIPITATION - JAEGER (1976) ANNUAL MEAN
CONTOURS AT 0.1.1.2.5.10.20 (SHADED OVER 5MM)
AVERAGE FROM 0Z ON 1/1 TO 0Z ON 365/12
SURFACE

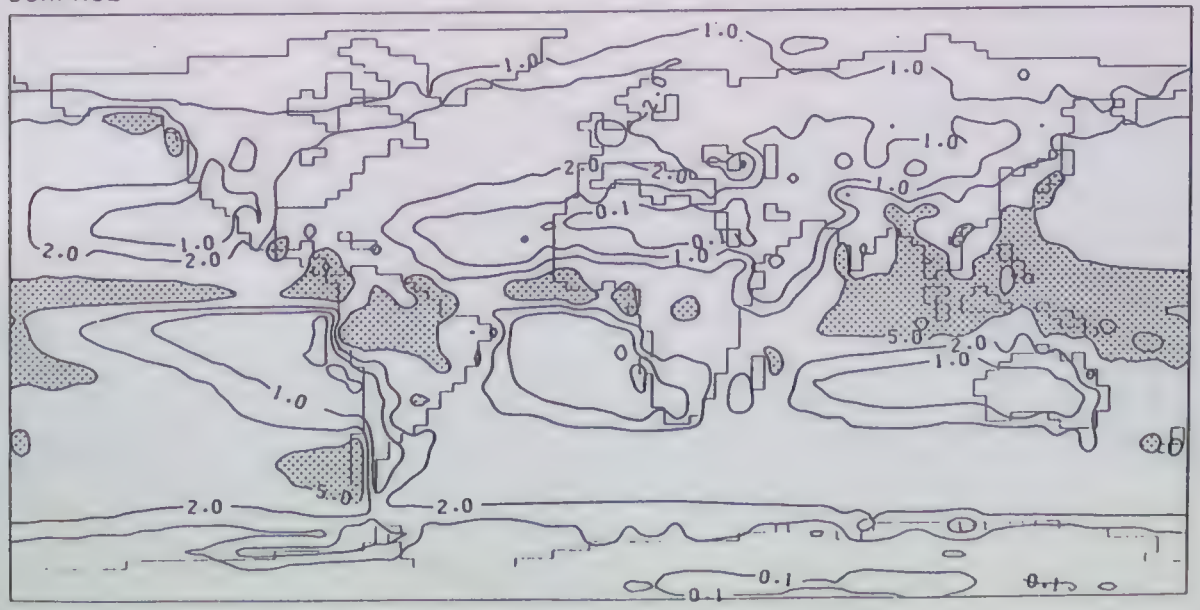

FIGURE 4c

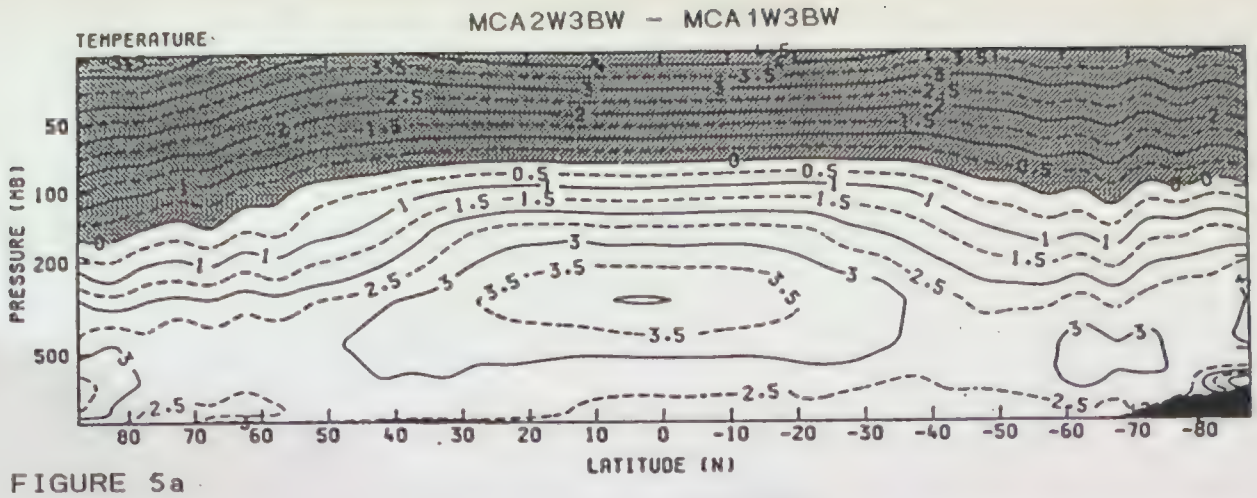

FIGURE 5a

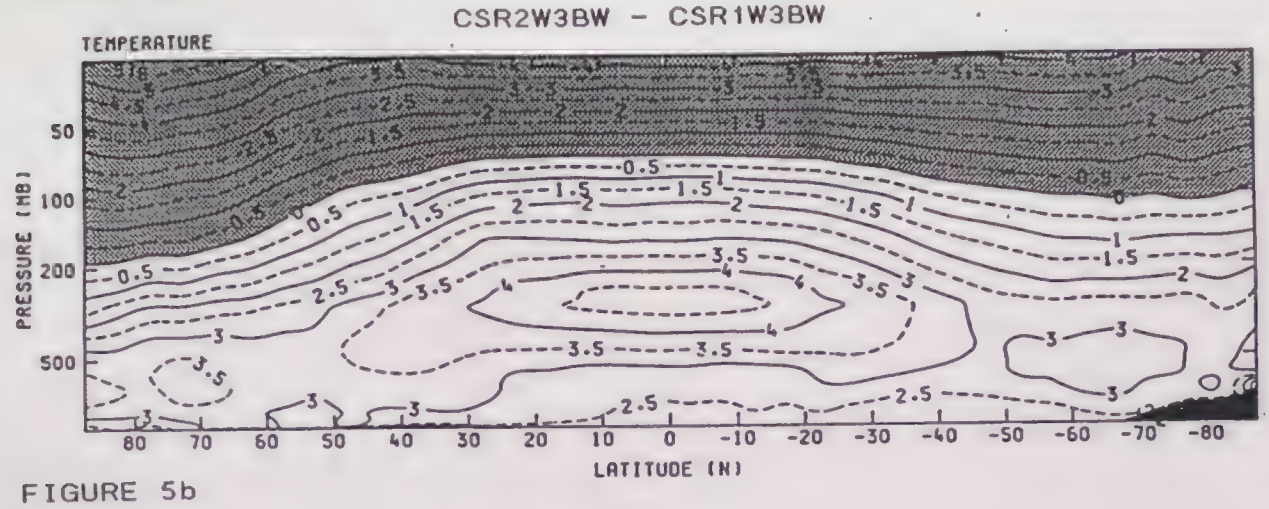

FIGURE 5b

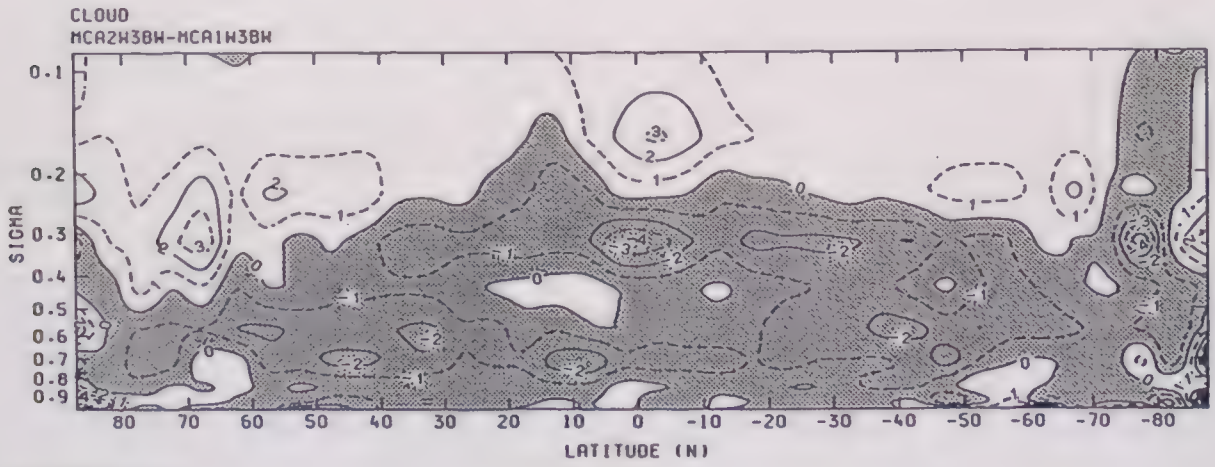

FIGURE 6a

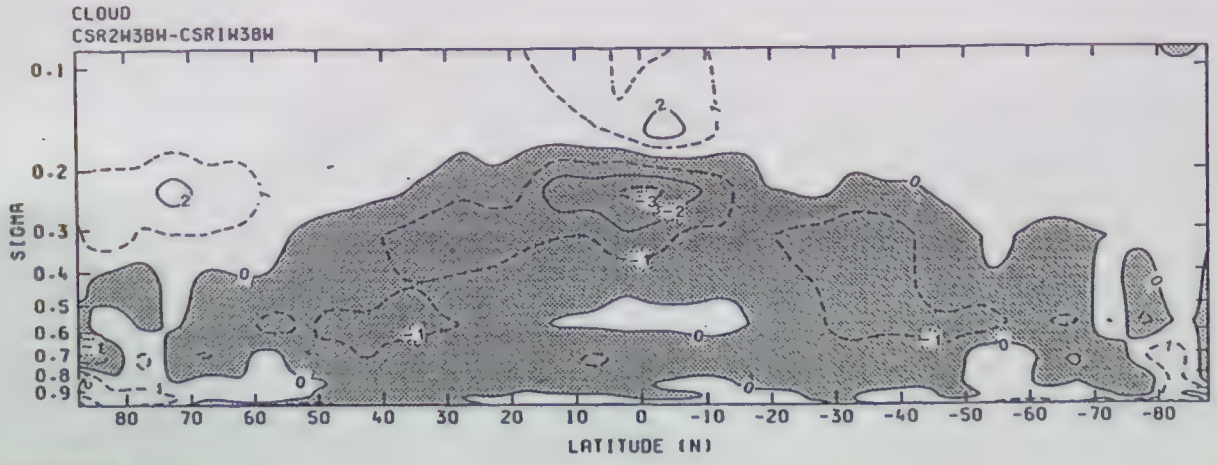

FIGURE 6b

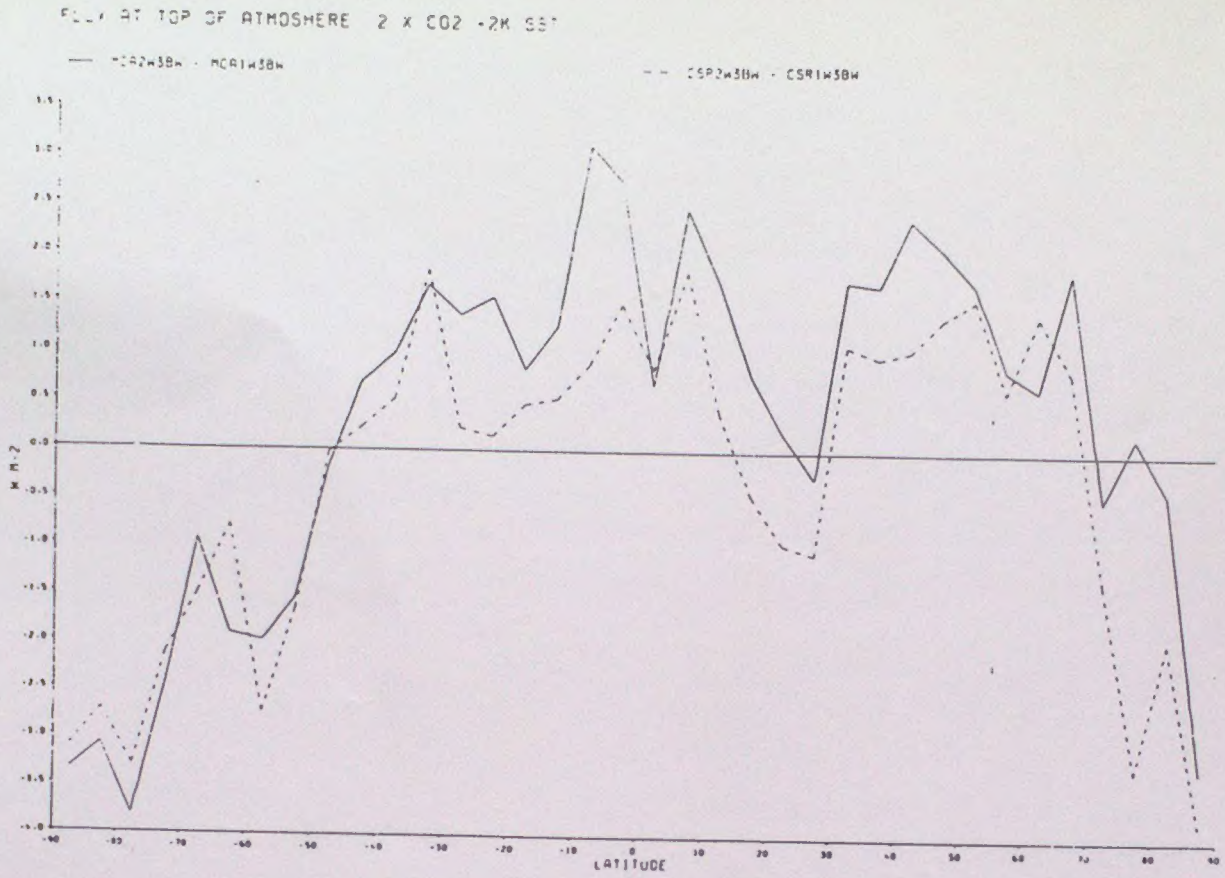

FIGURE 7a

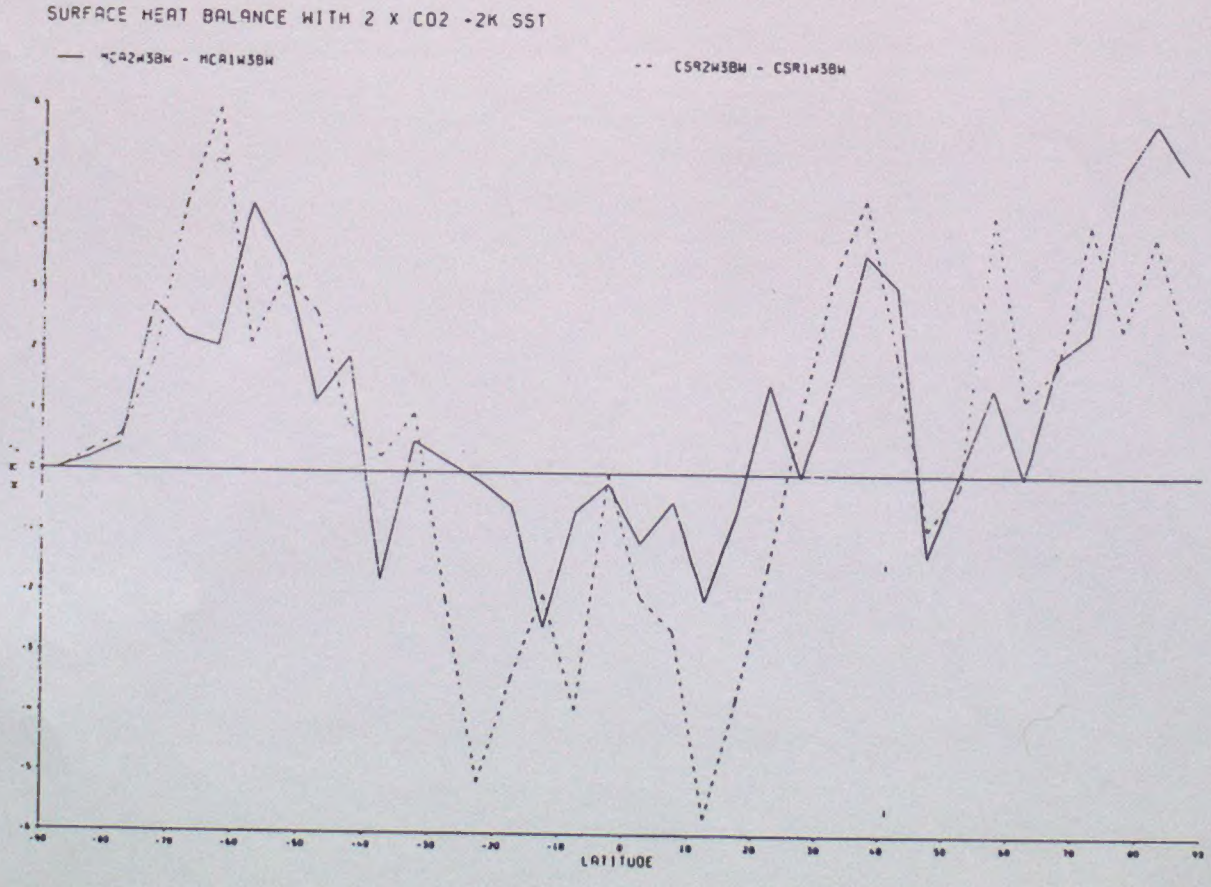

FIGURE 7b

DYNAMICAL CLIMATOLOGY TECHNICAL NOTES

DCTN 1 June 1984
A scheme for incorporating the thermodynamic sea-ice model into a coupled ocean-atmosphere model.
C Gordon and M Bottomley

DCTN 2 Sept 1984
The parametrization of the upper ocean mixed layer in coupled ocean/atmosphere models.
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S A Clough, M S Grahame and A O'Neill

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M S Grahame

DCTN 6 Sept 1984
Development of an improved GCM radiation scheme.
A Slingo and R C Wilderspin

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